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Process Modeling of Turn-Milling Using Analytical Approach

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Abstract

Turn-milling is relatively a new cutting process which combines two conventional manufacturing processes; turning and milling. This promising technology becomes an alternative to turning due to its advantages such as higher productivity and lower cutting temperatures, which provide longer tool life. Intermittent characteristics of turn-milling helps maintaining lower cutting temperatures and making high cutting speeds possible. In this study, the objective is to build a process model for turn-milling operation. Two possible methods used in turn-milling, orthogonal cutting and tangential cutting are considered. The developed model includes cutting geometry and force calculations. In addition, analytical expressions for circularity are presented as well. Finally, a comprehensive process model is obtained for both orthogonal and tangential turn milling operations. This model is used to compare different types of turn-milling operation and optimize the process. Experiments were conducted to verify the force model on a mill-turn CNC machine tool where the cutting forces were measured by a rotary dynamometer.

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1. Introduction

Turn-milling is a promising technology for machining of rotationally symmetrical parts with improved productivity. One of the important difference in turn milling is that cutting speed includes both tool and work piece rotations. The studies about turn-milling started in 1990 [1]. In this study Schulz et al. [1] divided the turn-milling operations into two groups: orthogonal and co-axial. It is stated that co-axial turn-milling can be used for both internal and external machining of rotationally symmetrical work pieces whereas orthogonal turn-milling can only be used for external machining.

Turn-milling offers several advantages. First of all, due to rotational movements of both tool and work piece, high cutting speed can be achieved in turn-milling operations. Furthermore high surface quality and low cutting forces are obtained. Additionally because of the

interrupted cutting, cutting temperature reduces which in turn reduces tool wear and increases tool life.

Although Schulz has considered only orthogonal and co-axial turn-milling operations, recent studies mostly focus on orthogonal and tangential processes. The main consideration in the previous research on turn-milling has been surface roughness. Choudhury et al. [2] studied orthogonal turn-milling and compared the surface roughness values with those obtained by standard turning. They claim that 10 times better surface quality can be achieved by turn-milling compared to turning. In another study again Choudhury et al. [3] investigated the surface roughness in orthogonal turn-milling and simulated it by using experimental design. Savas et al. [4] analyzed the surface roughness in tangential turn-milling and found that with tangential turn-milling very good surface quality which is comparable to ground surfaces can be achieved. In addition to surface roughness studies, Neagu et al. [5] investigated the kinematics of orthogonal turn-milling.

In this study Neagu et al. [5] dealt with roundness, cutting speed and tool functional geometry in orthogonal turn-milling. More recently Filho [6] investigated the cutting forces in orthogonal turn-milling by using a five axis machining center. Jiang [7] modeled the surface texture of the work piece machined by tangential turn-milling. These developments show that there is an increasing interest on turn-milling processes.

The objective of the present study is to develop models for process geometry, kinematics and mechanics as well as machined part quality in orthogonal and tangential turn-milling operations and tool. In accordance with this purpose the paper is organized as follows. First, the engagement limits and chip geometry are explained. Secondly, the cutting speed for both configurations is described. Then, circularity in turn-milling is formulated. Finally, cutting force calculations are presented with experimental verification.

2. Engagement Limits and Chip Thickness

In turn milling the chip is formed by combination of two motions: work piece rotation and feed in axial direction. As a result of this we have two different feed rates, circumferential and axial feed rates. Circumferential feed includes relative motion of tool and work piece rotations where degree of penetration is related to the ratio of tool and work piece rotational speeds. For the axial feed, the mechanism is similar to conventional milling where tool radius and feed (mm/rev) are important for the engagement limits.

Another consequence of simultaneous rotational and linear motions is that the trajectory of the tool on work piece is a helical one (see Fig 1). The helix angle of the tool path is determined by the magnitude of the circumferential and axial feed rates. Basically, if the circumferential feed is much larger than the axial feed, the helix angle becomes higher and vice versa. The value of helix angle can be found by:

$$\beta = \arctan \frac{(R_w - a_p) \tan \theta}{f(mm/rev)/(r_n z)} \quad (1)$$

$$\theta = \frac{2\pi}{z r_n} \quad (2)$$

where r_n is the ratio of n_t/n_w , n_w and n_t are the work piece and tool rotational speeds, respectively, and z is the number of cutting teeth on the tool. R_w is the radius of work piece, f is the feed per revolution and a_p is the depth of cut.

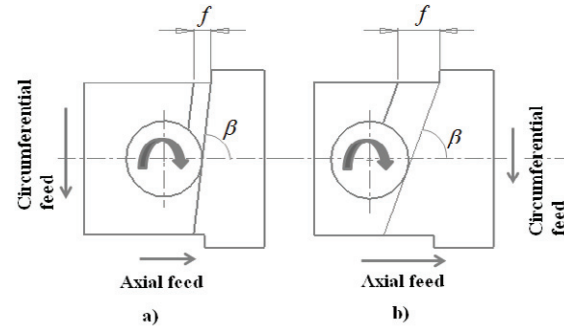


Fig. 1. Helical tool trajectory in turn milling (a) circumferential feed is high, axial feed is low (b) circumferential feed is low, axial feed is high

2.1. Orthogonal turn-milling

In orthogonal turn-milling the chip is formed by the action of side and bottom part of the cutting tool [6]. Fig 2 represents the steps while obtaining the uncut chip in orthogonal turn-milling case. Defining uncut chip geometry is an important step for modeling of cutting forces. The initial and the final position of the tool can be used to determine the uncut chip thickness [6]. The cross section of the uncut chip for orthogonal turn-milling process can be seen in Fig 3.

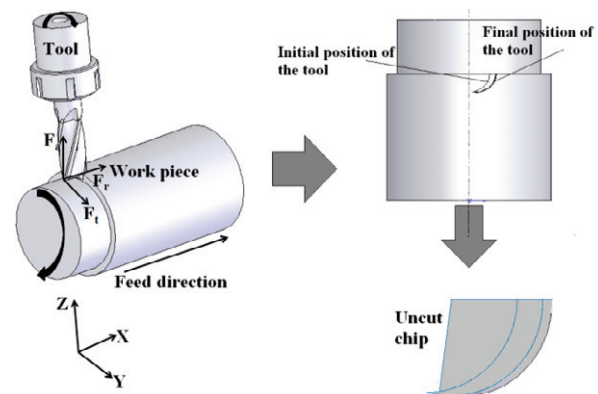


Fig. 2. Procedure for obtaining uncut chip geometry

The green area in Fig 3 represents the cross section of the uncut chip. Line 1-2 is the initial position of the cutting tool whereas line 1-3 is the final position of the cutting tool. In addition, line 2-2' is the side of the cutting tool at initial position whereas line 3-3' represents the side of the cutting tool in the final position. In reality, the tool doesn't rotate around the work piece, but it is easier to assume this way to simply the geometrical analysis. The angle between line 1-2 and 1-3, θ , represents the angular rotation of the cutting tool around the work piece. The angle θ is described as in equation (2).

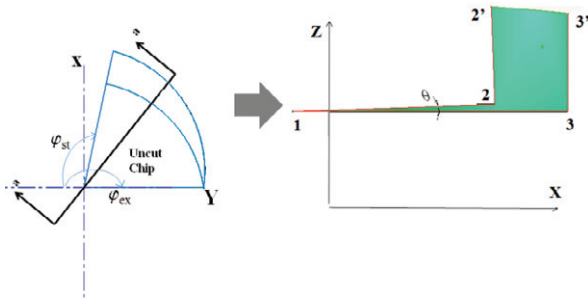


Fig. 3. The cross section of the uncut chip

From geometrical relations, line 1-2 can be defined by:

$$z(x) = \tan \theta \cdot x + \frac{(R_w - a_p)}{\cos \theta} \quad (3)$$

Line for 1-3 which defines the bottom of the final position of cutting tool can be represented by:

$$z(x) = (R_w - a_p) \quad (4)$$

The geometrical definition of line 2'-3' changes with respect to Y axis so the definition becomes:

$$z(x) = \sqrt{(R_w + y \cdot \tan \varphi)(R_w - y \cdot \tan \varphi)} \quad (5)$$

where φ is the immersion angle. In addition to these lines the points that are represented by 1, 2 and 3 should be defined in order to determine the limits of different regions in the geometry.

$$\begin{aligned} x_1 &= (R_w - a_p) \left(\frac{1}{\cos \theta} - 1 \right) \left(\frac{1}{\tan \theta} \right) \\ x_2 &= R_t - ((R_w - a_p) \tan \theta) \cos \theta \\ x_3 &= R_t \end{aligned} \quad (6)$$

where R_t is the radius of the cutting tool. Finally, it can be said that there are two different regions that represent the uncut chip. The first region is limited by lines of 1-2 and 1-3 and defined as:

$$h(x) = \tan \theta \cdot x + \frac{R_w - a_p}{\cos \theta} - (R_w - a_p) \quad (7)$$

The second region is formed by 2'-3' and line 1-3 and can be represented by:

$$h(x) = \sqrt{(R_w + y \tan \varphi)(R_w - y \tan \varphi)} - (R_w - a_p) \quad (8)$$

Equations above determine the chip geometry due to the

circumferential feed. In addition the tool translates in the axial direction forming chip in this direction as well. The chip thickness due to the axial feed is as follows:

$$\begin{aligned} h_a &= f_t \cdot \sin(\varphi) \\ f_t &= \frac{f(\text{mm/rev})}{r_n Z} \end{aligned} \quad (9)$$

Thus, the total instantaneous chip thickness in turn-milling can be defined as follows

$$h_i = h + h_a \quad (10)$$

The engagement limits for the configuration given in Fig 3 in orthogonal turn-milling process can be expressed as

$$\varphi_{st} = \frac{\pi}{2} + \arcsin \frac{R_t - f}{R_t} \quad (11)$$

$$\varphi_{ex} = \pi \quad (12)$$

One can calculate the chip thickness by using equations above. Fig 4 shows the effect of r_n on chip thickness variation where $a_p=0.6$ mm, $R_w=40$ mm and $R_t=5$ mm $f=0.4$ mm/rev. As it can be seen from the Fig 4 as the speed ratio decreases the chip thickness increases. From Fig 3 one can conclude that with increasing θ higher chip thickness values are obtained.

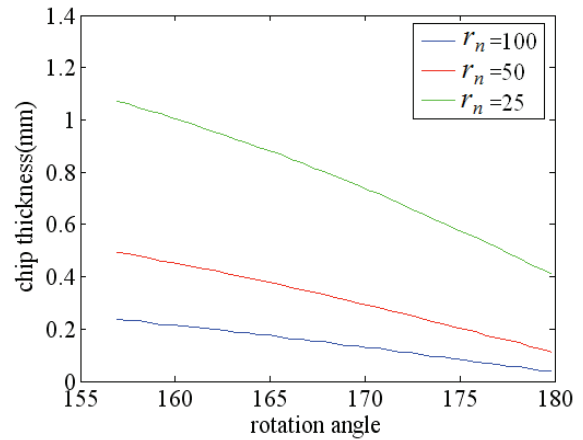
Fig. 4. Variation of chip thickness with the speed ratio, r_n

Fig 5 shows chip thickness variation with respect to r_d . It can be implied that chip thickness increases with decrease in the ratio r_d where $a_p=0.6$ mm, $n_w=5$ rev/min., $n_t=500$ rev/min and $f=0.4$ mm/rev.

2.1. Tangential turn-milling

In tangential turn-milling the chip is formed by the side of the cutting tool. The uncut chip can be determined by a similar procedure followed in the orthogonal case.

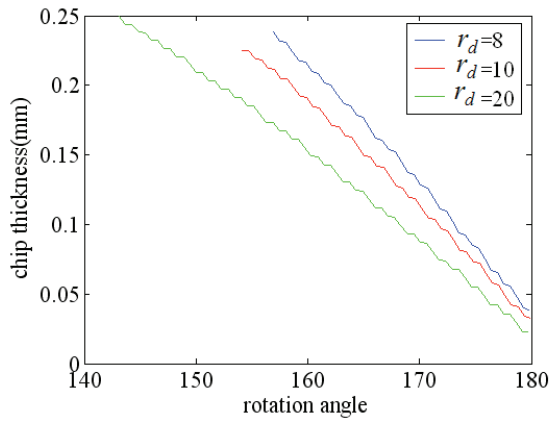


Fig. 5. Chip thickness with respect to diameter ratio, $r_d = D_w/D_T$.

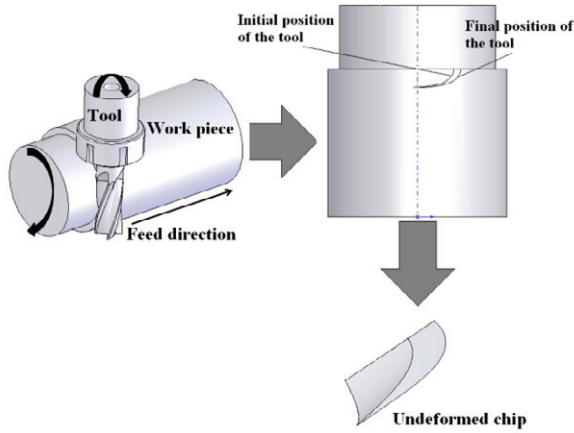


Fig. 6. The uncut (un deformed) chip in tangential turn-milling

Fig 6 shows tangential turn-milling operation and the uncut chip. Similar to the orthogonal case the green area in Fig 7 shows the cross section of the uncut chip. The angle between line 1-2 and 1-3 is again θ like in orthogonal case.

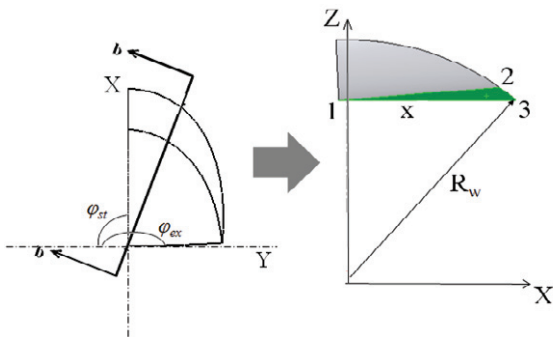


Fig. 7. The cross section of the chip in tangential turn-milling

In order to define the chip thickness, the geometrical expressions of the uncut chip should be derived. The line 1-3 can be defined as:

$$z(x) = R_w - [\sqrt{R_t^2 - y^2} - (R_t - a_p)] \quad (13)$$

As it is seen from the equation above, the length of the line changes with y . Line 2-3 can be defined as

$$z(x) = \sqrt{R_w^2 - x^2} \quad (14)$$

Line “1-2” can be defined as

$$z(x) = \tan \theta \cdot x + \frac{R_w - [\sqrt{R_t^2 - y^2} - (R_t - a_p)]}{\cos \theta} \quad (15)$$

In order to define the boundaries of regions mentioned above, the geometrical locations of points “1”, “2”, “3” should be known:

$$\begin{aligned} x_1 &= -\left(\frac{\sin \theta (R_w - [\sqrt{R_t^2 - y^2} - (R_t - a_p)])}{\cos \theta + 1} \right) \\ x_2 &= \cos \theta \sqrt{R_w^2 - (R_w - [\sqrt{R_t^2 - y^2} - (R_t - a_p)])^2} \\ x_3 &= \sqrt{R_w^2 - (R_w - [\sqrt{R_t^2 - y^2} - (R_t - a_p)])^2} \end{aligned} \quad (16)$$

Like orthogonal cutting instantaneous chip thickness is:

$$h_i = h + h_a \quad (17)$$

Finally the engagement limits can be defined as follows

$$\varphi_{st} = \frac{\pi}{2} - \arcsin \frac{f/2}{R_t} \quad (18)$$

$$\varphi_{ex} = \pi - \arcsin \frac{R_t - a_p}{R_t} \quad (19)$$

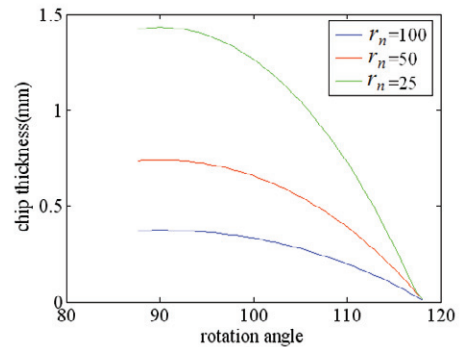


Fig. 8. Chip thickness with respect to r_n in tangential turn-milling

Like in orthogonal turn milling, the chip thickness

increases with decreasing r_n in tangential turn milling as it is seen in Fig 8 where $a_p=0.6$ mm, $R_w=40$ mm, $R_t=5$ mm and $f=0.4$ mm/rev.

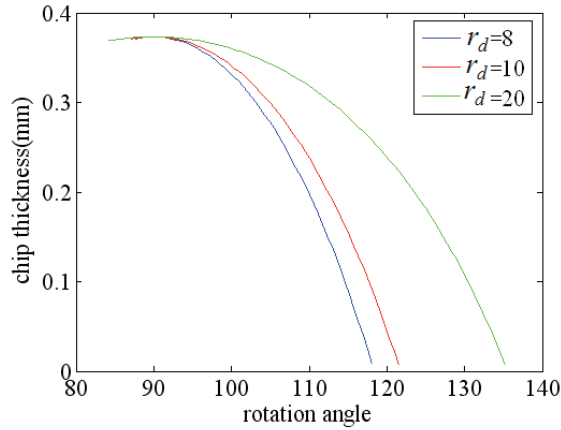


Fig. 9. Chip thickness with respect to r_d ratio in tangential turn-milling

Fig 9 shows the dependency of the chip thickness in tangential turn milling on r_d where $a_p=0.6$ mm, $n_w=5$ rev/min., $n_t=500$ rev/min and $f=0.4$ mm/rev. Since the engagement limits are related to the tool radius as explained above they vary with r_d .

3. Cutting Speed

In turn-milling both cutting tool and work piece rotate, and thus the result cutting speed is a function of both rotational speeds.

3.1. Orthogonal turn-milling

Fig 10 shows the schematic representation of orthogonal turn-milling and directions of tool and work piece velocities at the cutting point. In orthogonal turn-milling the cutting velocities of tool and work piece are on same plane as shown in Fig 9. So as the tool rotates the angle between tool and work piece velocity changes. The resultant velocity can be defined as follows:

$$\begin{aligned} \text{Relative Velocity} &= \overline{V_2} - \overline{V_1} \\ &= V_2 + V_1 \cos(90 - \varphi) \end{aligned} \quad (20)$$

$$V_1 = 2\pi(R_w - a_p)n_w$$

$$V_2 = 2\pi R_t n_t$$

3.1. Tangential turn-milling

Fig 11 shows the schematic representation of tangential turn-milling and directions of tool and work piece velocities. In tangential turn-milling the cutting velocities of tool and work piece are not on the same plane but on the planes that are perpendicular to each other as shown in Fig 11. Thus, for a non-helical tool as

the tool rotates the magnitude of the cutting velocity doesn't vary as it does in orthogonal case. However, for a helical tool the material will be fed into the cutting edge due to work and tool rotations in which case an average chip approach direction can be defined. In the following zero helix case is considered.

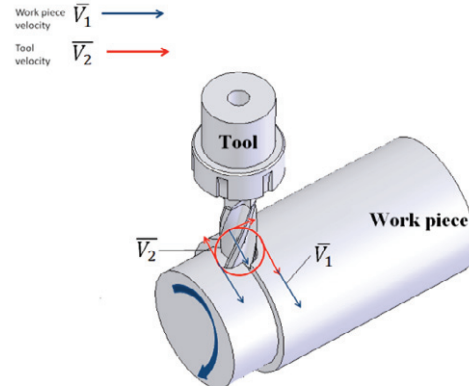


Fig. 10. Schematic representation of orthogonal turn-milling

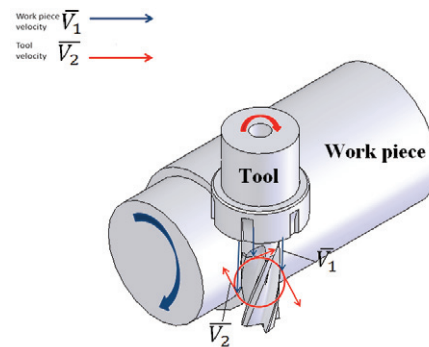


Fig. 11. Schematic representation of tangential turn-milling

The resultant velocity can be defined as follows:

$$V = 2\pi R_t n_t \quad (21)$$

As it is seen the definitions of cutting speeds for two cases are different. In Fig 12 there is a comparison for an arbitrary condition between orthogonal and tangential cases from cutting speed point of view. The green and blue curves represent orthogonal turn milling, in case of green curve work piece rotates clockwise, and which rotates counter clockwise in blue case. One can see that the cutting speed in tangential case is constant. In orthogonal case, on the other hand, the cutting speed varies with respect to the immersion angle. This result is important for cutting temperatures since cutting speed is the most important factor that affects the cutting temperature and tool wear.

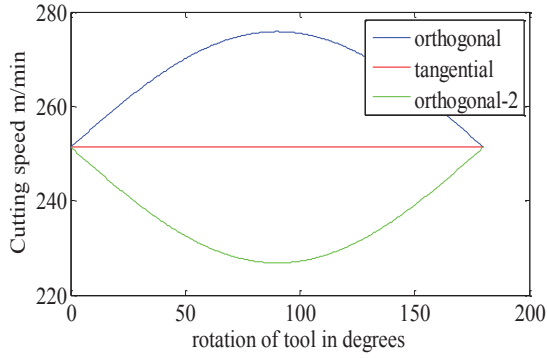


Fig. 12. Comparison of cutting speeds

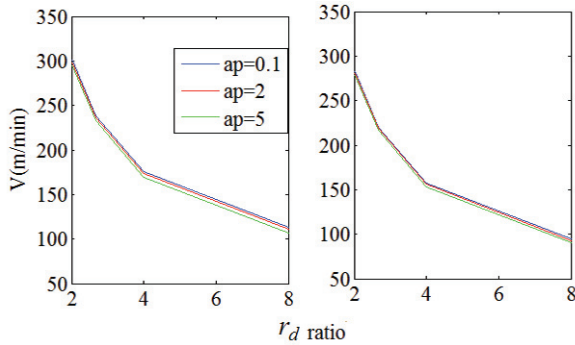


Fig. 13. Variation of maximum and average cutting speeds with tool and work piece radii.

Fig 13 shows the value of maximum and average cutting speeds for orthogonal turn milling. Maximum and average values of cutting speeds in orthogonal case decrease with r_d ratio. Also, it is seen that the depth of cut has no significant effect on cutting speed.

4. Circularity

Turn-milling operation (both orthogonal and tangential) doesn't produce an ideal circle. Since in turn-milling cutting tool and work piece rotate simultaneously, the resulting machined part cross section is a polygon as shown in Fig 14. The difference between the desired and the shapes can be denoted as OB-OA. The definition of circularity for orthogonal and tangential cases can be derived from the geometry as follows:

$$\begin{aligned} OA &= R_w - a_p \\ OB &= \frac{R_w - a_p}{\cos \theta} \\ OB - OA &= (R_w - a_p) \left(\frac{1}{\cos \frac{\theta}{2}} - 1 \right) \end{aligned} \quad (22)$$

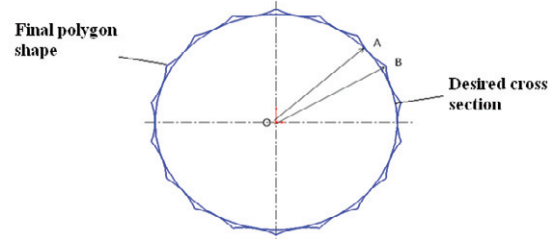


Fig. 14. Cross section of work piece produced in turn milling

As it is clearly seen from the equations above one can control the circularity in turn-milling through selection of process parameters. The ratio of tool and work piece rotational speeds and the depth of cut are the most significant factors influencing circularity.

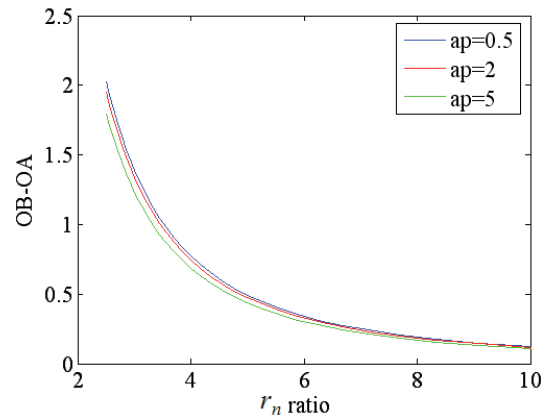
Fig. 15. Degree of circularity in turn milling with respect to depth of cut and r_n .

Fig 15 shows the effects of depth of cut and speed ratio, n_r , on the circularity. As it can clearly be seen the circularity strongly depends on the speed ratio where the effect of cutting depth is small. The finished product cross section converges to an ideal circle as the speed ratio is decreased, i.e. the tool rotates at a much higher rate than the work piece.

5. Cutting Forces

Using the chip thickness expressions developed in Section 2 cutting forces can be calculated according to mechanistic modeling described in [8].

Cutting forces can be determined by dividing the uncut chip into elements. The elemental cutting forces can be expressed as follows [8]:

$$\begin{aligned} dF_{t,j(\varphi,z)} &= [K_{tc} h_j(\varphi_j(z)) + K_{te}] dz \\ dF_{r,j(\varphi,z)} &= [K_{rc} h_j(\varphi_j(z)) + K_{re}] dz \\ dF_{a,j(\varphi,z)} &= [K_{ac} h_j(\varphi_j(z)) + K_{ae}] dz \end{aligned} \quad (23)$$

The elemental forces are integrated within the engagement zone to obtain the total cutting forces.

$$\begin{aligned} F_t(\phi_j(z)) &= \int_{z_{j,1}}^{z_{j,2}} dF_t(\phi_j(z))dz \\ F_r(\phi_j(z)) &= \int_{z_{j,1}}^{z_{j,2}} dF_r(\phi_j(z))dz \\ F_a(\phi_j(z)) &= \int_{z_{j,1}}^{z_{j,2}} dF_a(\phi_j(z))dz \end{aligned} \quad (24)$$

where $z_{j,1}(\phi_j(z))$ and $z_{j,2}(\phi_j(z))$ are the engagement limits of the in-cut portion of flute j [8].

In order to illustrate the behavior of cutting forces in turn-milling some representative simulation results are presented next. Fig 16 shows the tangential cutting forces for both orthogonal and tangential operations for the conditions given in Table 1.

Table 1. Cutting conditions used in comparing cutting forces

Cutting conditions	Value
R_w (mm)	40
R_t (mm)	5
f (mm/rev)	0.1
n_w (rev/min)	5
n_t (rev/min)	500
a_p (mm)	0.6
K_t (MPa)	536
z	4

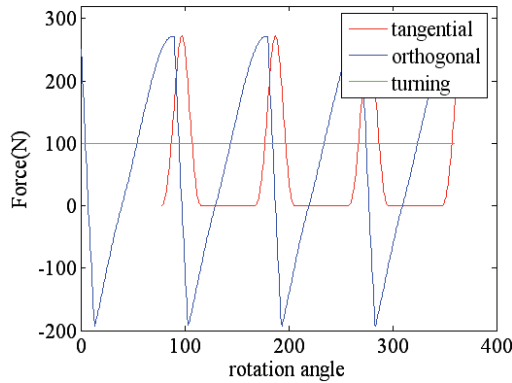


Fig. 16. Comparison of cutting forces

Fig 16 also shows that the maximum forces obtained in two different operations are almost the same although the immersions are different, i.e. in orthogonal case the immersion of the tool is larger. The maximum forces are same in two different operations because chip thickness definitions at that immersion angles are governed with same equation. In Fig 16 turning force can be seen for same MRR(material removal rate) with two turn milling operations. Additionally continuous behavior of classical turning and intermittent behavior of turn milling can be identified in Fig 16.

Fig 17 shows the maximum and average absolute forces with r_n for both cases. As it can be clearly seen from the Fig 17 both maximum and average absolute cutting forces decrease with r_n for both cases. Because increasing r_n ratio means decrease in θ value according to equation (2) and as it is explained above an decrease in θ value means an decrease in chip thickness according to Fig 2 that is why cutting forces decrease with r_n ratio.

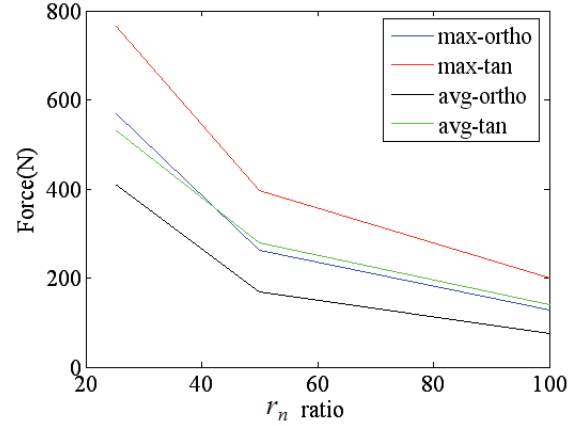


Fig. 17. Variation of tangential cutting forces with r_n .

Fig 18 shows the change in the maximum and average absolute forces with r_d . Maximum force in tangential turn milling remains same because maximum chip thickness does not change with r_d (see Fig 9). Decrease in both maximum and average absolute values in orthogonal turn milling can be explained by chip thickness variation in Fig 5. As it is seen from Fig 18 maximum and average values do not change with r_d for tangential turn milling

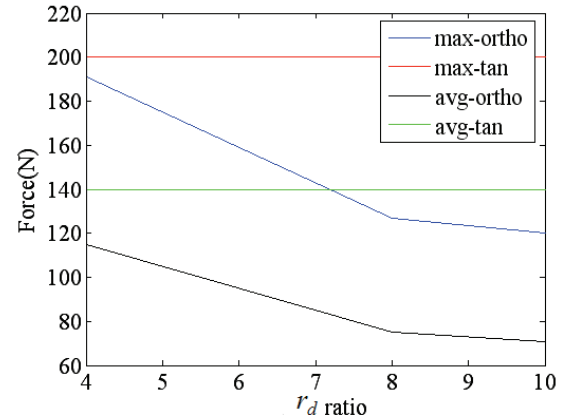


Fig. 18. Variation of tangential cutting forces with r_d

6. Experimental Results

Experiments were carried out cutting force model was conducted on a mill-turn machine tool [Mori Seiki NTX2000] to evaluate the process models developed in this study. The experimental setup can be seen in Fig 19

for cutting force measurements. Carbide milling tool has 10 mm diameter with 30° helix angle and 4 cutting teeth. Work piece is a 90 mm diameter 1050 steel. Cutting forces were measured by Kistler rotary force dynamometer.

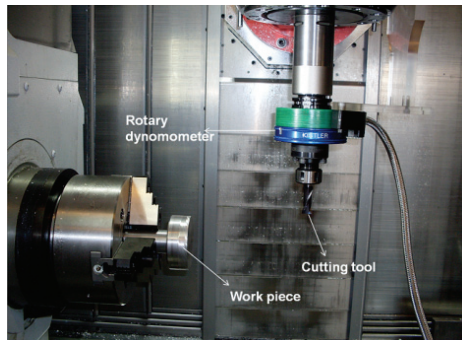


Fig. 19. Experimental setup

Experimental results are compared with those obtained by the force model for cutting conditions given in Table 2.

Table 2. Cutting conditions used in cutting force tests.

Cutting conditions	Value
Configuration	Orthogonal
R_w (mm)	45
R_t (mm)	5
f (mm/rev)	0.2
n_w (rev/min)	50
Number of teeth	4

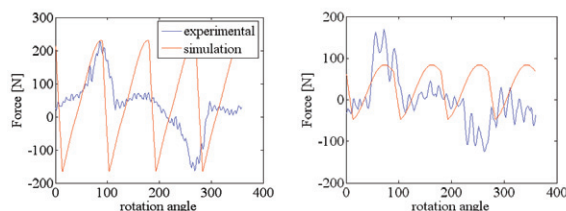


Fig. 20. Comparison between experimental and simulation results in X direction (a) $n_t=500$ rev/min (b) $n_t=1000$ rev/min

In Fig 20 the comparison between experimental data and simulation results are shown. As it can be seen from the variation of the peak forces in the measurements, there is a significant amount of run-out on the milling tool. This was mainly caused by the addition of an adaptor to clamp the dynamometer which had a different taper than the machine's spindle. The run-out is being tried to be reduced by precision grinding of this adaptor.

7. Results and Discussion

In this study geometry, kinematics and mechanics of the turn-milling operation are discussed orthogonal and tangential tool-part configurations. Firstly, the

engagement limits and the uncut chip was described and related equations were given. Then, the cutting speed which is important from efficiency point of view was explained. Next the circularity problem was mentioned and defined by equations. Finally the cutting forces were calculated according to uncut chip geometry by mechanistic modeling.

From the analytical formulations, simulation and experimental results the following conclusions can be drawn.

1. A model based on uncut chip thickness and engagement limits can predict the cutting forces in turn milling. The maximum and average forces decrease with r for both orthogonal and tangential cases. Additionally maximum and average forces in orthogonal case decrease with r_d whereas they remain constant in tangential case.
2. Cutting forces are affected by many parameters. One of the most important one in turn milling is the ratio of cutting speeds. The cutting forces decrease with the increasing speed ratio. Cutting force variation with the diameter ratio is also investigated. Maximum force in tangential turn milling remains constant with the diameter ratio. On the other hand in orthogonal turn milling the maximum forces decrease with the diameter ratio. Additionally average absolute forces in tangential turn milling remain constant with the diameter ratio whereas they decrease in orthogonal turn milling.
3. Cutting speed in orthogonal turn milling changes with respect to immersion angle since the circumferential speeds of tool and work piece are on the same plane. In orthogonal turn milling it matters whether the work piece rotates clockwise or counter-clockwise. If it is clockwise, the cutting speed has a minimum in one revolution of tool and vise versa. In tangential turn milling, on the other hand, circumferential speeds are on the perpendicular planes resulting in constant cutting speed (for non-helical tools).
4. Circularity is the one of the most important issues in turn milling, and strongly depends on the speed ratio. If the rotational speed ratio of the work piece to tool decreases, i.e. tool rotates faster, the cross section of work piece approaches an ideal circle.
5. Chip thickness evaluation is important from force calculation point of view. In this study chip thickness is obtained analytically in both orthogonal and tangential turn milling. In orthogonal turn milling as the speed and diameter ratios, i.e. r_n and r_d decrease, chip thickness increases. In tangential turn milling the chip thickness decreases with r_n and r_d as well. Furthermore engagements limits vary with the tool radius and feed per revolution.

6. The efficiency in machining is basically determined by MRR (Material Removal Rate). In turn milling since cutting speed is a function of both tool and work piece speeds MRRs can be achieved by selecting speeds accordingly.

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